Sensors and Actuators A 206 (2014) 159–164

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

A thermoelectric-based energy harvesting module with extended operational temperature range for powering autonomous wireless sensor nodes in aircraft☆

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ARTICLE INFO

Article history:
Received 14 September 2013
Received in revised form
25 November 2013
Accepted 25 November 2013
Available online 4 December 2013

Keywords:
Thermoelectric energy harvesting
Phase change material
Scaling of energy output
Wireless sensor nodes

ABSTRACT

This paper describes the performance improvement of an energy harvesting device for aircraft by increasing its operational temperature range. The thermoelectric energy harvesting device consists of two cavities each containing a different phase change material, acting as thermal mass. Thermoelectric generator elements (TEGs) are attached to the inner part of the fuselage and to the thermal mass. Therefore, an artificially enhanced temperature difference between the bottom and the top surface of the TEGs is created during take-off and landing. Different temperature profiles mimicking short/mid-range European flights are investigated. The performance in terms of efficiency, power-to-weight ratio and energy harvested is studied in detail, both by simulations and experimental data.

The following paper was published in less detail at the TRANSDUCERS 2013 under number 0532 with title *Performance of a low temperature energy harvesting device for powering wireless sensor nodes in aircrafts applications*

This manuscript is intended for the TRANSDUCERS 2013 special issue

1. Introduction

Maintenance is one of the largest expenses that a civil aviation company has to incur over the lifetime of an aircraft and can be as high as 18% of its total cost [1,2]. Nowadays, structural health monitoring (SHM) sensors can help placing the scheduled maintenance and checks further apart or even convert them to on-demand checks [3]. Sensors vary in type, from simple crack wire sensors, to multi-axial strain gauge sensors to acousto-ultrasound devices. Traditionally, wired solutions are used, which are reliable, but introduce weight and increase the design complexity of the aircraft. The targeted solution to that problem is wireless SHM. Batteries are good candidates for supplying power, but require frequent charging, hence negating the on-demand purpose of the concept. In addition, batteries have a limited operational temperature range with respect to aviation-related temperature characteristics when targeting advanced sensor applications [4].

Thermoelectric energy harvesting has proven its potential in a flight test campaign [5] and its suitability for use in low power, autonomous applications such as wireless sensor nodes for health monitoring purposes in aircraft [6]. The energy such devices capture, when driven through a power management module, is sufficient to power a sensor node and a wireless data transmission module for enough time to take measurements and transmit the results [7].

The scope of this paper is to investigate in details of the performance, flexibility, and scalability of a composite energy harvesting device and to maximize its worst case energy output under varying temperature conditions during aircraft operation.

2. Design aspects

The energy harvesting device described in this paper consists of a dual-cavity container, filled with two different phase change materials (PCMs) that act as thermal mass. This container is attached on one side of the thermoelectric generators (TEGs), while the other side of the TEG is fixed to a heat source, in this case the fuselage of the aircraft. The temperature difference across the two sides of the TEGs during take-off and landing is enhanced by the

☆ Selected Paper based on the paper presented at The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, June 16–20, 2013, Barcelona. Spain

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http://dx.doi.org/10.1016/j.sna.2013.11.036

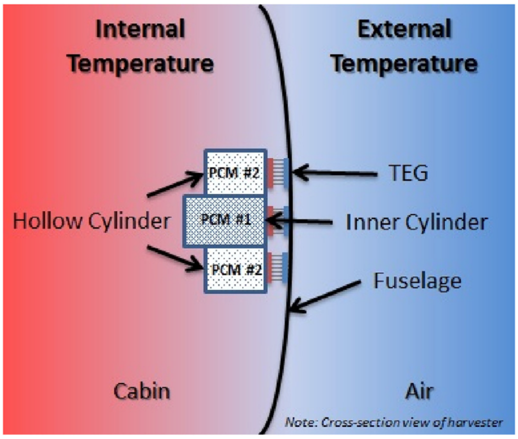


Fig. 1. Schematics of the thermoelectric harvesting device containing two PCMs when attached to the fuselage of an aircraft.

latent heat and the large heat capacity of the PCMs thus enhancing the energy output [7]. This concept is illustrated in Fig. 1.

PCMs offer material-specific and defined phase change temperatures. This can be a limiting factor when broad temperature conditions are to be encountered, as the case in aircraft, thus the idea of applying multiple PCMs is introduced. Previous versions of the multi-PCM harvester consisted of two separate closed cavities for the inner and hollow cylinder, made from a single material (stainless steel, copper or 3D printed ABS plastic) and their performance has been assessed in [8].

For the present version of the harvester, the two cylinders have been combined in a single body of PMMA which offers low thermal conductivity and low density. The volumes of the two containers are 30 ml for the inner cylinder and 30 ml for the hollow cylinder, respectively. The bottom of the cylinders is made of copper and fixed to the PMMA with a cyanoacrylate adhesive. Copper has a high thermal conductivity and hence, most of the heat flux goes through it via the TEGs to the fuselage and *vice versa*. Four TEGs were installed below the inner cylinder and electrically connected in series. Below the hollow cylinder, eight TEGs were placed and again electrically connected in series. The TEGs (TEG 1-9.1-9.9-0.8/200 [9]) were made by Eureca, and the Seebeck coefficient and internal resistance for each of them is 27 mV/K and 8.85 Ω, respectively. Load resistors matching the total internal resistance of each of the clusters were installed in parallel to each TEG cluster as explained in Section 3. Furthermore, heat pipes in the form of thin copper fins are used to enhance the heat flux from the PCM to the fuselage [10]. A schematic of the whole set-up is shown in Fig. 2a. A prototype of the thermoelectric harvester device is built as close as possible to the theoretical model used for the simulations, and is shown in Fig. 2b.

Table 1
Physical properties of the materials used.

Material	T_m [°C]	C_p [kJ/kgK]	k [W/mK]	ρ [kg/m^3]	ΔH [kJ/kg]
Water	0	4.2	0.5	1000	333
E-11 [9]	−11	3.55	0.57	1090	301
Copper	1084	0.38	401	8940	176
PMMA	160	1.46	0.17	1170	–

The PCMs used in the harvester are distilled water and E-11 provided by PCM Products Ltd. [11]. Water possesses the best thermal properties at its phase change temperature, whereas PCM E-11 promises to offer one of the highest latent heat values available at its phase change temperature of −11 °C. The physical properties of the materials used are summarized in Table 1.

The PCMs are examined under the same temperature profiles, simulating different, European, short to medium-range flight patterns. Four ground temperatures are selected, representing "average" (20 °C), "high" (30 °C), "low" (−5 °C), and "optimum" (10 °C) conditions, wherein both materials undergo full phase changes. Under the "optimum" and "average" temperature profiles, both PCMs undergo a phase change. Due to the super-cooling effect, which is explained in detail in Section 5, the "optimum" temperature range is selected throughout this paper as the best example for demonstrating the impact of phase changes of both PCMs on the energy output. The temperature difference between maximum and minimum temperature, i.e. ground and cruising altitude, was set at 40 °C. The corresponding temperature profiles are shown in Fig. 3.

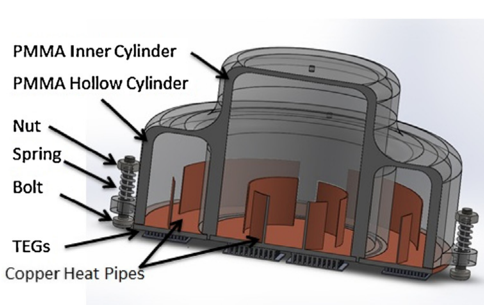
3. Theoretical background

The electric power output of a thermoelectric harvesting device strongly depends on the efficiency of the TEGs used. Furthermore, the efficiency depends on the ΔT across the TEG, defined as the ratio between the heat flux converted into electrical power. The theoretical equation of the efficiency of a TEG is according to [12]

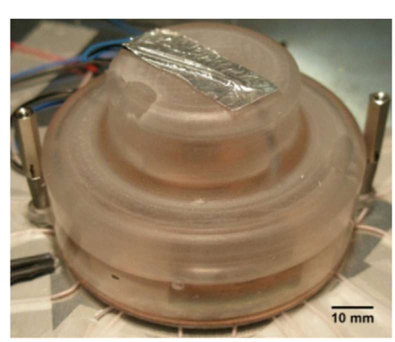
$$\eta = \frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{(T_h-\Delta T)}{T_h}} \times \frac{\Delta T}{T_h} \tag{1}$$

where, Z is the figure of merit, T the average temperature and T_h the temperature on the hot side.

The cold and hot sides in this application scenario are calculated based on the average temperature across the two sides [13]. The overall efficiency is calculated based on the figure of merit, which is taken from the datasheets of the TEGs used [9]. The efficiency



(a)



(b)

Fig. 2. (a) Schematic, cross-sectional view on the thermoelectric device, indicating the main components, (b) Actual prototype, with copper bottom plate, heat pipes, and PCMs.

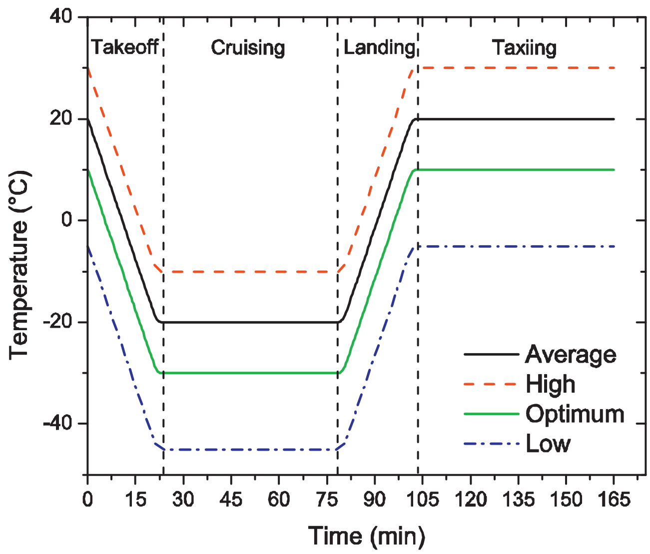


Fig. 3. The four different fuselage temperature profiles used.

for all the temperature profiles ranges from 0.47 to 0.49% since it depends strongly on the materials of the TEGs.

The energy stored in a PCM undergoing a phase change is

$$Q = \int_{T_h}^{T_m} mC_{p,l}(T)dT + m\Delta H + \int_{T_m}^{T_c} mC_{p,s}(T)dT \quad (2)$$

where, m, $C_{p,l}$, $C_{p,s}$ is the mass and specific heat capacity in the liquid and solid phase, respectively. T_c and T_m denote the temperature on the cold side and the phase change temperature.

The theoretical calculations for the energy stored in a PCM per gram and the energy output per gram of the device described above are presented in Table 2 (assuming maximum ΔT and thus maximum η for each temperature range at the TEG).

The conversion of temperature difference into electricity is based on the Seebeck equation, $V_{TEG} = \alpha(T)\Delta T$, where α is the Seebeck coefficient. For small temperature changes, the Seebeck coefficient is assumed to be independent from temperature. In addition, using a load resistance, R_l, equal to the total internal resistance of the TEGs ($R_i = R_l$), the power output is maximized, as is the energy, which can be written as

$$E = \int_0^t P_{out} dT = \int_0^t \frac{V_{TEG}^2}{R_i} dT = \int_0^t \frac{\alpha^2}{4R_i} \Delta T^2 dT \quad (3)$$

The energy output at maximum power output with respect to the mass of the device provides an important figure for the avionic applications. This figure is the power to weight ratio and can be calculated according to mean power output (energy over the total flight duration) per unit mass.

Table 2
Energy stored in a PCM per gram versus the theoretical harvestable energy per gram within a complete flight cycle. The temperature ranges are described above.

Temperature range	Energy stored in PCM (J/g)		Harvestable energy (J/g)	
	Water	E-11	Water	E-11
High (+30 °C to −10 °C)	959.33	284.00	4.54	1.34
Average (+20 °C to −20 °C)	917.33	866.00	4.38	4.14
Optimum (+10 °C to −30 °C)	874.67	842.67	4.22	4.06
Low (-5 °C to −45 °C)	166.67	806.67	0.81	3.94

Finally, the heat pipes introduced in this design increase the overall efficiency of the device up to 10% [10]. The heat flux from the TEGs to the PCMs and *vice versa* is increased since more surface with high thermal conductivity is in contact with the PCM. In addition, the low thermal conductivity of the walls compared to the high conductivity of the bottom part increases the overall efficiency as the ratio of the thermal conductivity of the TEGs with respect to the walls is very high, as reported in [10]. Further investigations of heat pipe characteristics and their impact on the performance will be performed in the near future.

4. Simulation results

COMSOL Multiphysics and its "Heat Transfer in Solids" module are used to evaluate the performance of the harvesting device. The finite element method (FEM) model is 2D-axisymmetric, which reduces the computation effort and time. The overall thermal contact resistance as well as the heat flux towards the environment are found experimentally and introduced in the model. The contact resistance dominates the actual temperature difference which is present at the TEG. To minimize the influence of surface-related imperfections of the TEGs and of the bottom plates, a thermal interface material is used which is implemented in the FEM model as well. Similarly, the heat flux towards the environment depends strongly on the materials and according to literature is found experimentally [14]. Fig. 3 shows the temperature profiles that were selected for the simulations and experimental testing. They were applied as a "temperature" boundary condition on the surface simulating the external fuselage temperature. The average temperature of the lower and upper surface of the TEG's in the model was used along with the Seebeck coefficient found in the datasheets to calculate the voltage output and finally the power and energy output.

The FEM model was created to investigate the most efficient placement of PCM in the inner and hollow cylinder, thus maximizing the energy output. PMMA as a container material has such a small thermal conductivity that it minimizes any exchange of heat between the PCMs. Simulations demonstrate that PCM placement when considering a volume for each PCM of 15 ml has a low impact on the energy output of the device. Table 3 shows the results of two simulations labeled as #1 (where the inner and hollow cylinders were filled with water and E-11 respectively) and #2 (where the inner and hollow cylinders were filled with E-11 and water respectively). The "average" and the "optimum" range energy output are similar for both PCM placements. However, it seems that simulation #1 is performing better than simulation #2 in the "high" temperature range and *vice versa* for the "low" temperature range. Further explanations are described in Section 5.

Furthermore, the simulated energy output values given in Table 3 are evaluated against experimental results, which are shown in Table 4. In general, the deviation of energy from the experimental results is less than 5%. Due to the super-cooling effect, which is further discussed in the next Section 5, the simulations for the "high"and "low" temperature ranges differ more than for those labeled as "average" and "optimum", as shown in Table 4. The discontinuous and semi-random nature of the effect, i.e. the sharp increase in temperature during phase change, makes it very difficult to simulate numerically with high accuracy. Therefore, an accurate simulation of the super-cooling effect is not pursued in the simulations.

5. Experimental results

Experimental tests are conducted in a climate chamber mimicking real flight profiles. In more detail, the change of the fuselage

Table 3
Simulation results for PCM placement.

Temperature range	Simulation #1			Simulation #2		
	Inner (J) water	Hollow (J) E-11	Total (J)	Inner (J) E-11	Hollow (J) water	Total (J)
High (+30 °C to −10 °C)	20.21	10.43	30.64	15.22	27.02	42.24
Average (+20 °C to −20 °C)	32.40	35.20	67.6	33.48	33.22	66.7
Optimum (+10 °C to −30 °C)	35.51	35.66	71.17	33.81	34.31	68.12
Low (−5 °C to −45 °C)	16.69	27.81	44.5	23.64	13.15	36.79

temperature on an Airbus test aircraft is about 0.050 K/s [15]. Due to operational constraints, the climate chamber can achieve a constant temperature gradient of 0.067 K/s, which is used as input parameter for both the simulations and the experiments. The experimental methodology that was followed matched that of [16]. The bottom of the harvester in the climate chamber is oriented parallel to the ground plane, thus being fixed horizontally.

5.1. A “typical” temperature profile

Fig. 4 illustrates the temperature profiles of the harvester under the “optimum” temperature range with 15 ml of PCM in each cylinder. The inner and the hollow cylinder are filled with equal volumes of water and E-11, respectively. Take-off lasts for the first 17 min. of the profile. Almost immediately after the aircraft reaches cruising altitude, the super-cooling effect takes place and can be seen at around 18 min. As shown in Fig. 4, the FEM model executes the phase change at precisely the specified temperature. In the climate chamber, however, this change happens almost 5 °C below the actual phase change temperature of the PCM.

Super-cooling is used to describe the temperature of a material when it has passed its freezing temperature without undergoing a solidification process. The presence and intensity of this effect depends, however, on the composition of the PCM and is generally stronger for purer materials like distilled water and less dominant in solutions like E-11 [17], as was observed in the climate chamber experiments. As soon as a PCM has been super-cooled and passed a critical temperature, rapid crystallization occurs and its latent heat is released over a short time interval. This sudden release of latent heat significantly increases the PCM's internal temperature, thus enhancing the energy output. This behavior is illustrated in Fig. 4a and b, respectively.

After the latent heat has been released, the temperatures of the PCMs gradually reach thermal equilibrium with the fuselage (during the “cruising time” period–from the 18th min. to the 100th min.). A similar but reversed behavior is observed during landing and taxiing, while the PCMs melt. Melting is more gradual than solidification because it only affects the outer boundary of the PCM being converted to liquid instead of its entire mass.

5.2. PCM placement

Under the “average” and “optimum” temperature profiles, both PCMs undergo a phase change as their respective phase change temperatures are within these temperature ranges. On the other hand, in the “high” temperature range, only water undergoes a phase change and E-11 acts as sensible heat storage medium, hence the energy output for E-11 is very low compared to that of water. Similarly, under the “low” temperature range, only E-11 undergoes a phase change, and thus water, serving as a sensible heat storage medium, contributes only a few joules to the total energy output. Table 4 summarizes all the energy outputs for the inner and hollow cylinder, obtained experimentally.

Once the FEM model was calibrated for the experimental results under the different temperature profiles, the placement of the PCMs was investigated. Simulations showed that PCM placement does not play a very significant role in the energy output (simulation results are illustrated in Table 3).

Heat, like electricity, follows the path of lowest resistance. This fact makes a great amount of the theoretically harvestable energy unavailable for energy conversion as it does not flow through the TEGs to and from the fuselage, but through the outer surface of the container to and from the environment. For the different temperature ranges the efficiency of the device ranges between 49–56% of the total harvestable energy and is comparable with previous designs [7].

The power-to-weight (PtW) ratio for the “optimum” temperature range is calculated taking the energy output up to the 150th min into account. After the 150th min. and until the system reaches thermal equilibrium, energy output is less than 0.3 J. The total weight of the device including TEGs, screws, and the PCMs (with 15 ml of each PCM) is 95 g. The total energy harvested is 67.38 J and thus the PtW ratio is calculated to be 0.079 W/kg, when water and E-11 is placed on the inner and hollow cylinder respectively.

5.3. Scaling effect

The “optimum” temperature profile was selected as a basis to quantify the impact of different amounts of PCMs on the energy output. The PCM volume for both cylinders was simultaneously varied from 5 to 23 ml, whereas the latter value is considered as the maximum volume that they can contain while allowing for a 10–15% volume expansion during solidification. The total harvested energy as well as the energy per gram is illustrated in Fig. 5.

Increasing the volume of the PCMs enhances the energy output. However, a saturating behavior is observed above 15 ml, as only the height is directly affected at a given bottom plate, thus increasing the surface area not being in contact with the TEGs. This fact decreases the efficiency of the device, as a higher amount of energy flows parasitically through the side walls of the container instead of through the TEGs.

Table 4
Experimental energy outputs with 15 ml of PCM in the two different placement configurations.

Temperature range	Experiment #1			Experiment #2		
	Inner (J) water	Hollow (J) E-11	Total (J)	Inner (J) E-11	Hollow (J) water	Total (J)
High (+30 °C to −10 °C)	30.11	12.81	42.92	9.53	34.22	43.75
Average (+20 °C to −20 °C)	34.50	33.91	68.41	28.69	39.54	68.23
Optimum (+10 °C to −30 °C)	34.23	35.49	69.72	30.16	39.62	69.78
Low (−5 °C to −45 °C)	8.62	31.12	39.74	22.63	8.36	30.99

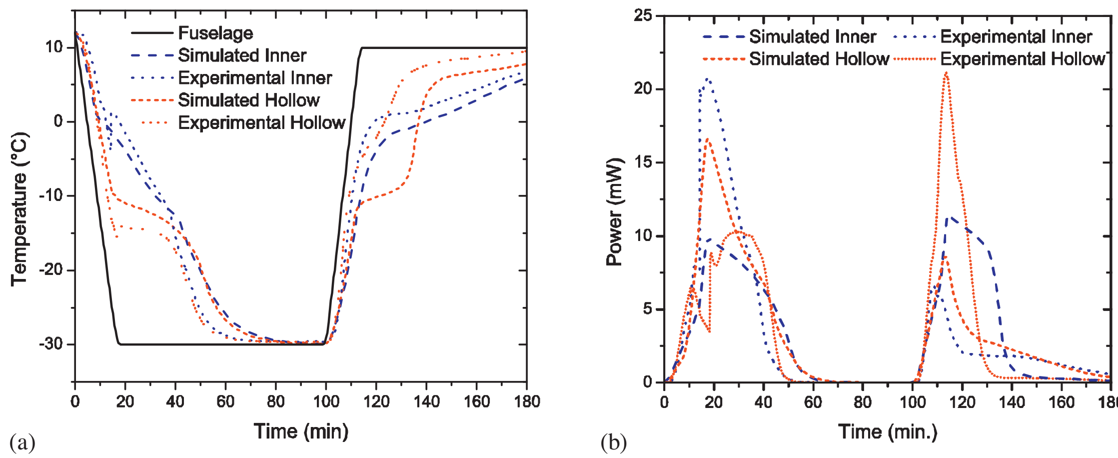


Fig. 4. (a) Simulated and experimental temperature profiles under the "optimum" temperature profile, (b) simulated and experimental power profiles when exposing the fuselage, inner and hollow cylinder to the "optimum" temperature profile.

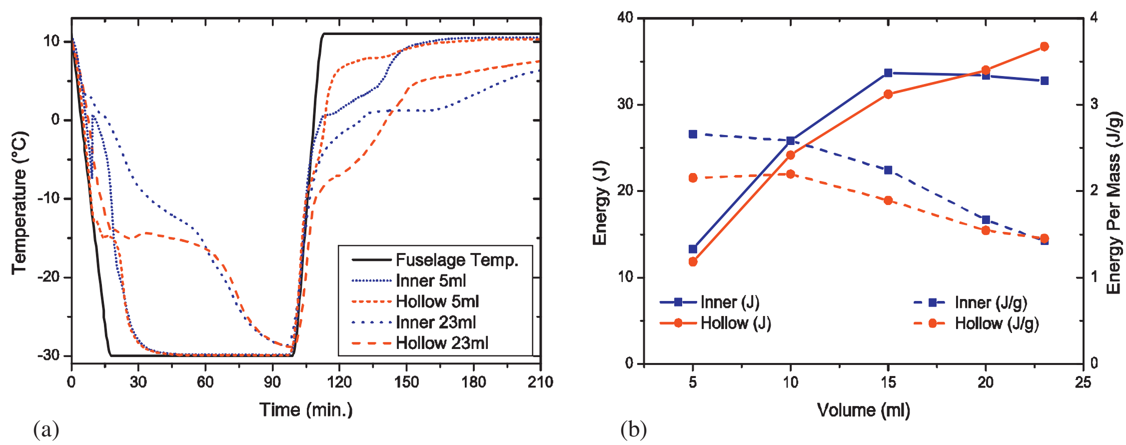


Fig. 5. a) Temperature profiles for two different configurations (i.e. 5 and 23 ml of PCM on each cylinder), (b) Total energy and energy per mass harvested during the experiments.

Additionally, for this specific device geometry, the necessary time period until a full cycle (liquid-solid-liquid/takeoff-cruising-taxiing) has been completed and increases substantially with 5 ml requiring only 90 min. and 23 ml requiring more than 210 min. However, the temperature difference across the TEGs and consequently the output voltage after the 160th min. for the 23 ml PCM configuration is too low to be used for harvesting purposes.

It should be noted that the duration of the cruising and taxiing phases were increased to allow for complete solidification and melting of the PCM volumes above 15 ml.

The scaling of PCM volume of this device suggests that what are its operational limits and what should be carefully considered when designing a harvester for a specific application. The energy output of a device is, of course, a key figure, but often it is not the only factor which should be taken into account. The energy per gram of PCM is also critical, ensuring that the device is operating at a satisfactory efficiency level.

The information on temperature as well as PCM volume scaling can act as fundamental guidelines in designing a thermoelectric energy harvester using PCMs. Given specific application requirements, a harvester fitting many different operational conditions can be fabricated, ranging from very small and lightweight devices, operating in a very narrow temperature environment with small energy requirements, to larger devices, with broad temperature ranges and greater energy outputs.

The design of a thermoelectric harvester with a PCM as a thermal mass is very challenging. For the determination of parasitic effects like the equivalent heat resistance and the heat flux lost to the ambient, experimental data are needed and have to be implemented in the simulation model in order to predict precisely the energy output. The experimental methodology that was followed matched that of [16]. However, some problems arose during testing. Small deviations in PCM volume (<±0.5 ml) were encountered. Additionally, there are always climate chamber temperature fluctuations (≤±0.3 °C), as stated in the specifications. Furthermore, material degradation due to the corrosiveness of E-11 against copper was observed on the bottom plates of the container. Finally, the supercooling effect is very unpredictable and can have a profound effect on the energy output from one experiment to the next. As such, a deviation of 10% between two sets of experiments is considered acceptable.

6. Conclusions and outlook

The thermoelectric harvesting device proposed in this paper has shown great potential. An investigation in terms of effective temperature range for a given amount of PCM (15 ml) as well as the impact of different PCMs in the two containers on the energy output was performed. In addition, scaling up and down in terms of PCM volume was further tested and basic conclusions concerning the experimental procedure were drawn.

As was shown by simulations, the placement of a PCM in the inner or hollow cylinder does not have a significant impact on the performance of the device. Independent of the temperature ranges investigated the minimum harvested energy is more than 30.99 J and under optimum conditions can be as high as 69.78 J, when 15 ml of each PCM are used. This amount of energy is sufficient to power up a wireless sensor [5].

The low overall weight of the device (≈95 g) provides the opportunity for high power-to-weight ratios. In addition, the efficiency which is around 56% of the total harvestable energy, compared with the theoretically calculated values, is similar to previous designs [7]. However, the consistent behavior within the different temperature ranges is the strongest advantage of this device, along with its low weight and the low thermal conductivity of the PMMA.

Experiments and simulations show that the device can be significantly scaled up or down in key domains, such as effective temperature, the volume, and the energy output, matching best to the requested flight duration. Based on these results it is indicated which parameters need to be considered when designing a thermoelectric harvester.

During the experimental tests, E-11 was found to be corrosive to the copper at the bottom of the harvester which might lead to early device failure, in addition to performance degradation. For that reason, different protective layers are under investigation and/or a redesign of the harvester, including corrosion-resistant materials for the bottom parts. Furthermore, container geometry optimizations, minimizing the total exposed surface area for a given PCM volume are considered. In addition, TEGs with a higher Seebeck coefficient in the targeted temperature range will further increase the overall efficiency of the device.

Acknowledgments

This work has been partially funded by the German Ministry of Economics (LuFo Project: Technologien für neuartige elektronische Luftfahrtsystem Ansätze (NELA) (No. 20Y1104C)). The authors would like also to thank Mr. Reiner Briechle and Mr. Johann Zeeh from the Analytical Laboratory in the University of Applied Sciences in Isny, Germany for the help on analyzing the PCMs.

References

[1] D. Gorinevsky, 5th International Workshop on Structural Health Monitoring, Honeywell Laboratories, Stanford, CA, September 2005.
[2] Bureau of Transportation Statistics, Office of Airline Information, 1200 New Jersey Avenue, SE, Washington, DC 20590, June 2009, http://www.bts.gov/oai.
[3] J.-M. Dilhac, et al., Crossfunctional design of wireless sensor networks applied to aircraft health monitoring, in: In International Workshop on Structural Health Monitoring, Stanford, United States, 2009.
[4] A. Pasquier, I. Plitz, S. Menocal, G. Amatucci, A comparative study of Li-ion battery, supercapacitor and nonaqueous asymmetric hybrid devices for automotive applications, J. Power Sources 115 (2003) 171–178.
[5] A. Elefsiniotis, D. Samson, T. Becker, U. Schmid, Investigation of the performance of thermoelectric energy harvesters under real flight conditions, J. Electron. Mater. 42 (7) (2013) 2301–2305.
[6] T. Becker, M. Kluge, J. Schalk, K. Tiplady, Ch. Paget, U. Hilleringmann, T. Otterpohl, Autonomous sensor nodes for aircraft structural health monitoring, IEEE Sens. J. 9 (11) (2009) 1589–1595.
[7] D. Samson, M. Kluge, T. Becker, U. Schmid, Wireless sensor node powered by aircraft specific thermoelectric energy harvesting, Sens. Actuator. A 172 (1) (2011) 240–244, 2011.
[8] A. Elefsiniotis, N. Kokorakis, T. Becker, U. Schmid, Design and Material Aspects for Thermoelectric Energy Harvesting Devices in Aircrafts, SPIE Microtechnologies 2013, Grenoble, France, 2013.
[9] EurecaMesstechnikGmbh. TEG1-9.1-9.9-0.2-100 data sheet. http://www.eureca.de/pdf/cooling/seebeck-elements/TEG1-9.1-9.9-0.2_100.pdf, accessed 10 June 2009.
[10] D. Samson, M. Kluge, T. Becker, U. Schmid, Optimization of a heat storage device for an aircraft specific thermoelectric power generator, in: Proceedings of the ECT 2010, Como, Italy, 22-24 September 2010, pp. 115–119.
[11] Phase Change Material Products Limited. http://www.pcmproducts.net/files/PlusICE%20Range-2013.pdf, PlusICE Phase Change Materials.
[12] M.E. Kiziroglou, D. Samson, T. Becker, S.W. Wright, E.M. Yeatman, Optimization of heat flow for phase change thermoelectric harvesters, Power MEMS 2011 (2011) 454–457.
[13] D. Samson, Energy Harvesting in Aircraft with Special Focus on Thermoelectrics, Vienna University of Technology, October 2011, Ph.D. thesis.
[14] Foundation Coalition, "Heat transfer applications in solids", Chapter 7, http://www.foundationcoalition.org/resources/en/engr214/Chapter7.pdf
[15] D. Samson, T. Otterpohl, M. Kluge, U. Schmid, T. Becker, Aircraft-specific thermoelectric generator module, J. Electron. Mater. 39 (9) (2010) 2092–2095.
[16] A. Elefsiniotis, N. Kokorakis, Th. Becker, U. Schmid, Performance of a low temperature energy harvesting device for powering wireless sensor nodes in aircrafts applications, in: Proceedings of the 17th International Conference on Solid State Sensors and Actuators, Transducers 2013, Barcelona, 2013, pp. 2276–2279.
[17] D. Feltham, M. Worser, Similarity solutions describing the melting of a mushy layer, J. Cryst. Growth 208 (2000) 746–756.

Biographies

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